Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Surface Waveguide Topologies Supporting Both TM- and TE-Mode with the Same Phase Velocity

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[1]University of Electronic Science and Technology of China, China
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Abstract: Surface waveguides (SWGs) are a class of open-boundary structures with the capability of guiding surface waves which are intimately bound to the surface of the structure[1]. One of the most commonly occurring type is the planar structures consisting of periodic sub-wavelength elements. Due to the capability of controlling the propagation path of surface waves (SWs), SWGs have been employed for the applications of electromagnetic scattering alteration, cloaking, absorbing, as well as antenna applications in the terms of modulated reactance surfaces, holographic surfaces and lenses.

An SWG structure supports SWs that are polarized in a transverse electric (TE) mode, a transverse magnetic (TM) mode, or a combination of a TM and a TE mode depending on the geometric structure of the surfaces[2]. SWG structures that support dominantly TM mode or TE mode have been studied for years and employed to design holographic surfaces for applications like leaky-wave radiation and field focusing. However, these structures are sensitive to the polarization and therefore limitations exist due to such polarization sensitivities. For example, it is challenge to get a centrally symmetric focused field when illuminated by a horizontally polarized field [3]. For holographic antennas, a narrow symmetric beam is also hard to achieve when excited by a horizontally polarized field. As a result, the aperture efficiency is reduced. Therefore, one significant challenge is to make a SWG structure that is insensitive to the polarization of given fields.

In this abstract, we introduce two kinds of SWG topologies that can support both TM and TE modes with the same phase velocity [4]. The proposed SWG structures are constructed by a double-layer FSS. The top- and bottom-layer FSS of the first class SWG are formed by the isotropic periodic elements. The two layers can dominantly support TM mode and TE mode, respectively. For the second type of SWG topology, the top and the bottom layers have the same geometry and are rotated 90^o with respect to the normal direction of the surface. In terms of the configuration of the each layer, the conducting strips are continuous in one direction and discontinuous in the other orthotropic direction. Therefore, for a single layer, it dominantly supports TM mode in one direction and TE in the orthotropic direction. In particular, a loop-wire

configuration and a modified Bow-Tie-like configuration are designed and analyzed to represent the two kinds of topologies. It is demonstrated that the two types of SWG structures can support both TM and TE modes by virtue of simulation and measurement.

Keywords:
Surface waveguides, dispersion, periodic structures, artificial materials, surface waves

Reference:

1. R. E. Collin, *Field theory of guided waves*, New York: MaGraw-Hill Book Company, Inc, 1960.
2. B. Fong, J. Colburn, J. Ottusch, J. Visher, and D. Sievenpiper, "Scalar and tensor holographic artificial impedance surfaces," *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3212–3221, Oct. 2010.
3. X. Wang, Y. B. Li, B. G. Cai and T. J. Cui, "Simultaneous controls of surface waves and propagating waves by metasurfaces," *Applied Physics Lett.* 105, 121603, 2014; doi: 10.1063/1.4896540.
4. Mei Li, Shao-Qiu Xiao, Jiang Long, Dan Sievenpiper, "Surface Waveguides Supporting Both TM Mode and TE Mode with the Same Phase Velocity," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 9, 2016.

Mei Li received the B.S. degree in electronic information science and technology from the Chengdu University of Information Technology, Chengdu, China, in 2010 and the Ph.D. degree in radio physics from the University of Electronic Science and Technology of China, Chengdu, China, in 2016. She was a visiting Graduate Student with the Applied Electromagnetics Research Group, University of California, San Diego, La Jolla, CA, USA, from 2014 to 2016. Her current research interests include reconfigurable antennas, phased arrays, artificial electromagnetic structures, and holographic metasurfaces.

Shao-Qiu Xiao received Ph.D. degree in Electromagnetic field and Microwave Engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2003. From January 2004 to June 2004, he was with UESTC as an Assistant Professor. From July 2004 to March 2006, he was with the Wireless Communications Laboratory, National Institute of Information and Communications Technology of Japan (NICT), Singapore, as a Researcher with a focus on planar antenna and smart antenna design and optimization. From July 2006 to June 2010, he was with the UESTC as an Associate Professor and currently, he is working with the UESTC as a Professor. He has authored/coauthored more than 160 technical journals, conference papers, books and book chapters. His current research interests include planar antenna and phased array, microwave passive circuits and time reversal electromagnetics.

Jiang Long received his B.S. and M.S. degree from Zhejiang University, Hangzhou, China, in 2007 and 2010, respectively, and the Ph. D. degree at University of California, San Diego, La Jolla, CA, USA, in 2015. He is currently an RF Engineer with Skyworks Solution Inc., Woburn, MA, USA. His current research interests include non-Foster circuits in antenna/microwave applications, including non-Foster circuit loaded active fast-wave waveguides, broadband metasurfaces, broadband antennas, and active microwave components. Dr. Long received the IEEE MTT-S Graduate Fellowship in 2015.

Dan Sievenpiper joined the UCSD faculty in 2009. He received his BS in 1994 and his PhD in 1999 from UCLA, where he studied photonic crystals and periodic structures, and invented the high impedance electromagnetic surface. After graduation, Dan joined HRL (the former Hughes Research Laboratories) in Malibu, CA. During the following 10 years, he developed new electromagnetic structures, with an emphasis on small, conformal, tunable, and steerable antennas. Dan held a variety of technical positions at HRL, including serving as the director of the Applied Electromagnetics Laboratory. In 2008, Dan was awarded the URSI Issac Koga Gold Medal. In 2009, he was named as a Fellow of the IEEE. In 2010, Dan was elected to the IEEE Antennas and Propagation Society Administrative Committee. Dan has more than 50 issued patents and more than 50 technical publications.

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Outline

- I Introduction
- II Theoretical Analysis
- III Topology I
- IV Topology II
- V Conclusion

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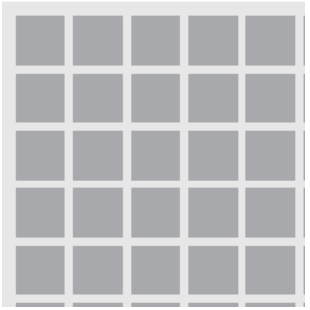
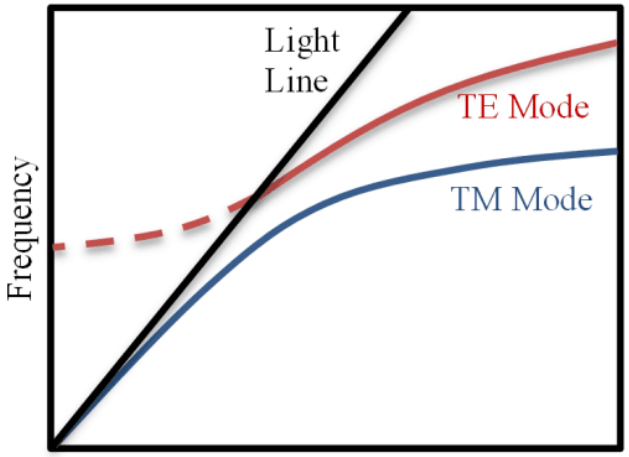
1. Introduction

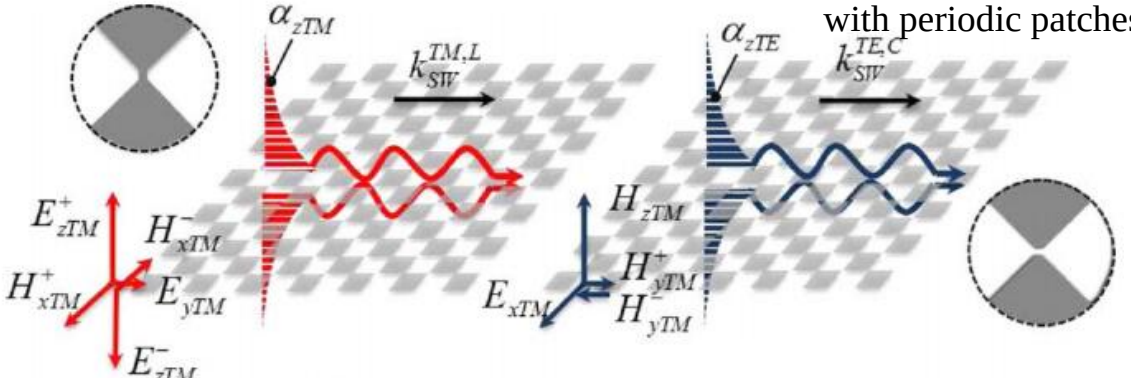
Surface waveguides (SWG) are a class of open-boundary structures with the capability of guiding surface waves (SWs), which are intimately bound to the surface of the structure. One of the most commonly studied type is the planar structures consisting of **periodic subwavelength elements**.



e.g. grounded slab loaded with periodic patches



Typical dispersion curves of SWG



For a geometrically self-complementary SWG, TM mode is dominantly supported when the vertexes are connected, and TE mode otherwise.

- **SWG structures these structures are generally sensitive to the polarization direction (support a dominant TM or TE mode) and therefore limitations exist due to such polarization sensitivities.**
- **Therefore, one significant challenge is to create a SWG structure that is insensitive to polarization (support both TM and TE modes with the same phase velocity).**

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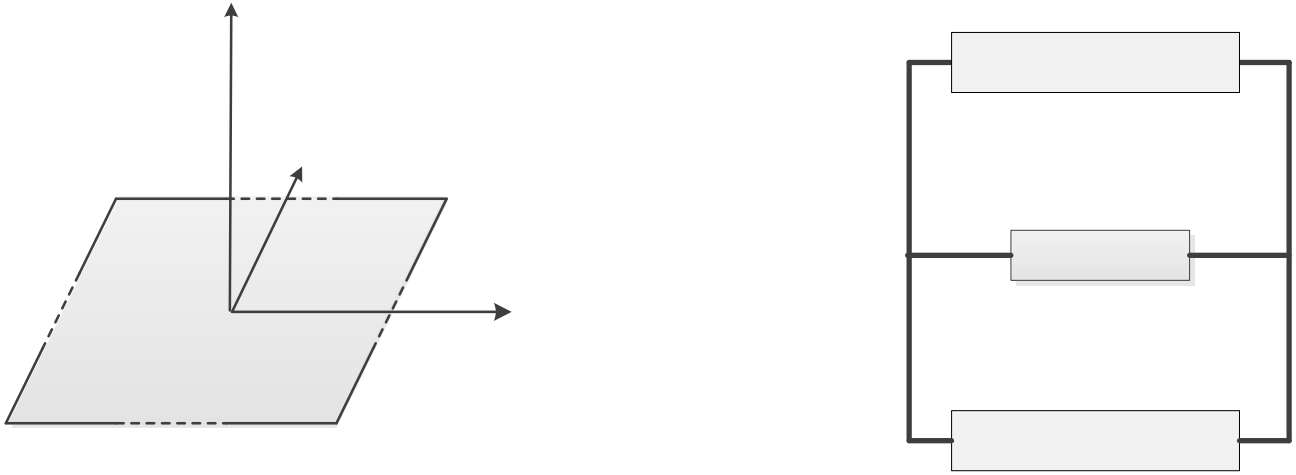
2. Theory analysis (1)



(a) (b)

Fig. Equivalent transmission line for transverse resonance analysis. (a) Infinite large SWG impedance sheet placed in the free space. (b) Transmission-line model for the SWG.

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2. Theory analysis (2)

The SW field on an SWG is characterized by an exponential decay $e^{-k_{z0}z}$ away from the surface and having the usual propagation function $e^{-jk_x x}$. Here, ${k_{z0}}^2 = {k_x}^2 - {k_0}^2, k_{z0} > 0$ and k_0 is the wave number in the free space above the surface.

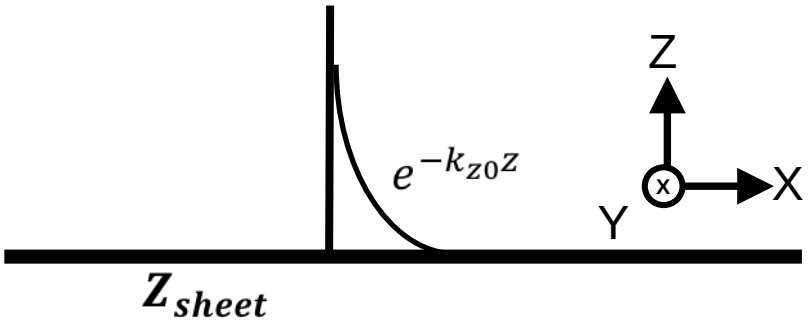

Fig. Surface wave propagating on an SWG.

$$\begin{cases} \Phi = \varphi_0 e^{-jk_x x} e^{-k_{z0}z} \\ E_{TM} = \left(\eta_0 \frac{k_x k_{z0}}{k_0}, 0, -j\eta_0 \frac{k_x^2}{k_0}\right)\Phi \\ H_{TM} = (0, jk_x, 0)\,\Phi \\ E_{TE} = (0, -jk_x, 0)\Phi \\ H_{TE} = \left(\frac{k_x k_{z0}}{\eta_0 k_0}, 0, -j\frac{k_x^2}{\eta_0 k_0}\right)\Phi \end{cases}$$

TM and TE wave impedances:

$$\begin{cases} (Z_0)_{TM} = \frac{E_x}{H_y} = -j\eta_0 \frac{k_{z0}}{k_0} \\ (Z_0)_{TE} = -\frac{E_y}{H_x} = j\eta_0 \frac{k_0}{k_{z0}} \end{cases}$$

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2. Theory analysis (3)

According to the transverse resonance condition:

$$(Z_0)_{TM}^{-1} + (Z_{sheet})^{-1} + (Z_0)_{TM}^{-1} = 0$$

TM mode

$$Z_{sheet} = 2j\eta_0 \frac{k_{z0}}{k_0}$$

AND

$$(Z_0)_{TE}^{-1} + (Z_{sheet})^{-1} + (Z_0)_{TE}^{-1} = 0$$

TE mode

$$Z_{sheet} = -2j\eta_0 \frac{k_0}{k_{z0}}$$

- **Conclusion: In order to support a TM mode propagation along an SWG structure, the surface impedance should have inductive reactive term. By the same manner, in order to support a TE surface wave, the reactive part of the surface impedance must be capacitive.**

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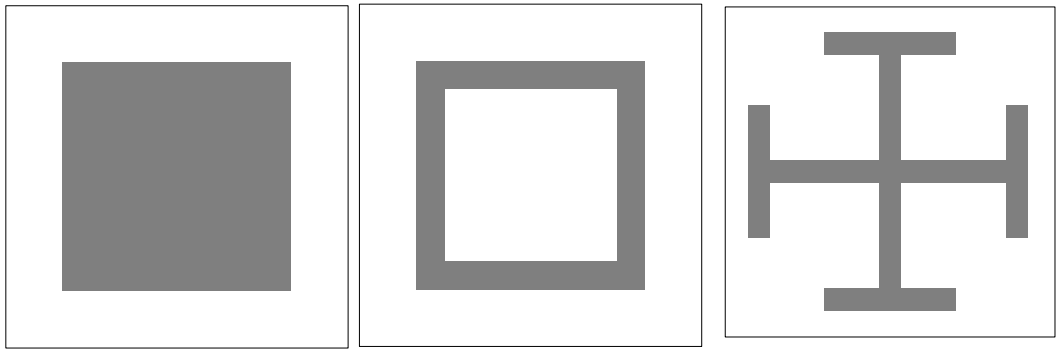
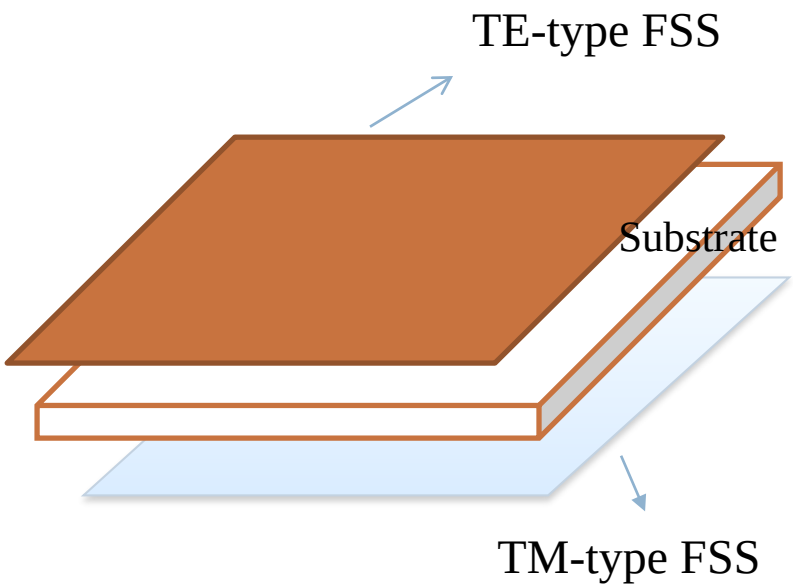
3. Topology I (1)

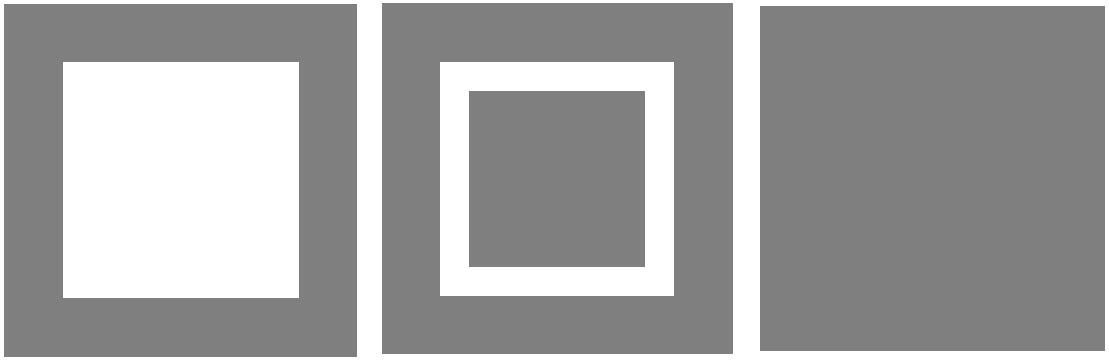
Three typical FSS elements supporting TE modes



(a) square patch (b) square loop (c) Jerusalem cross



Three typical FSS elements supporting TM modes



(a) grid (b) ring slot (c) ground

Topology configuration: Combination of a TE-type FSS and a TM-type FSS

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3. Topology I (2)

Loop-Wire Unit Cell Design

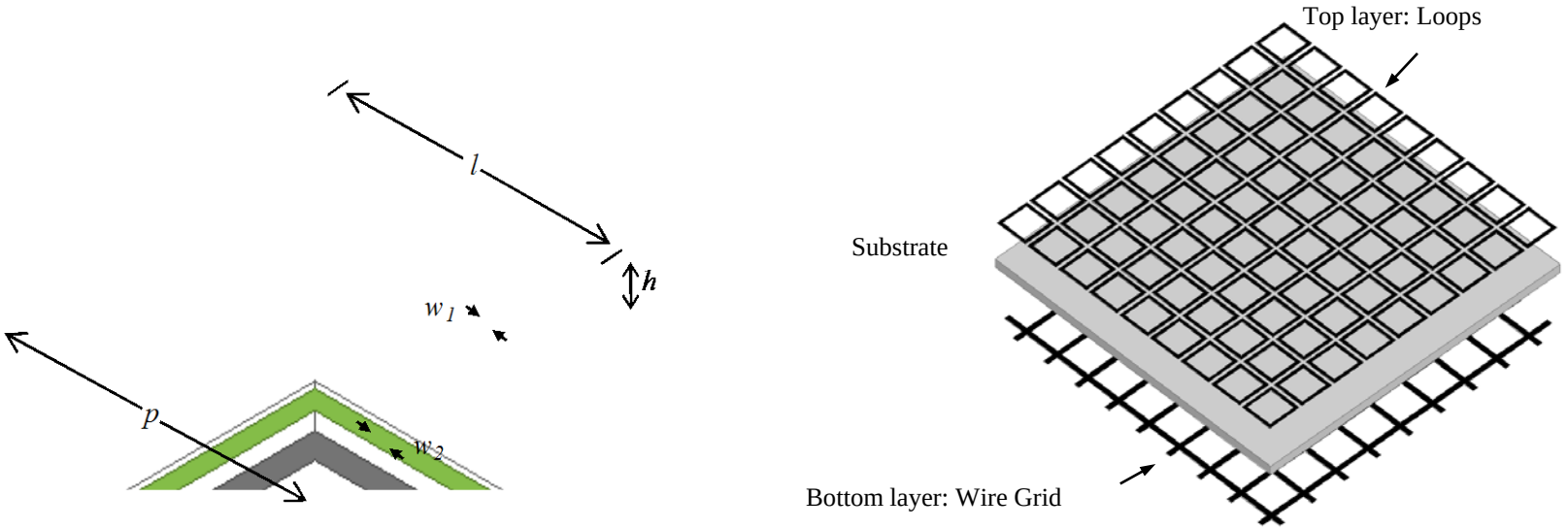

Fig. Loop-wire unit cell and a small portion of its SWG. (a) Loop-wire unit cell geometry. (b) SWG consisting of the loop array on one side and wire grid on the other side.

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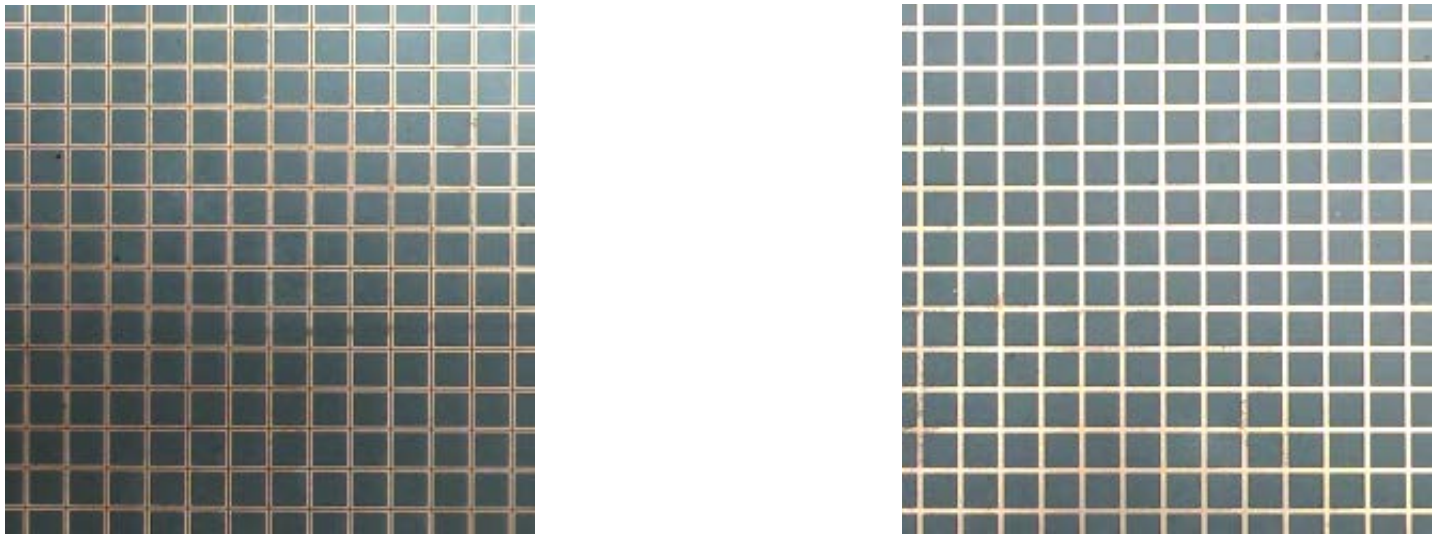
3. Topology I (3)

Fabrication



(a) (b)

Fig. Photograph of a session of the finite-size surface. (a) Top side: loop FSS. (b) Bottom side: wire-grid FSS.

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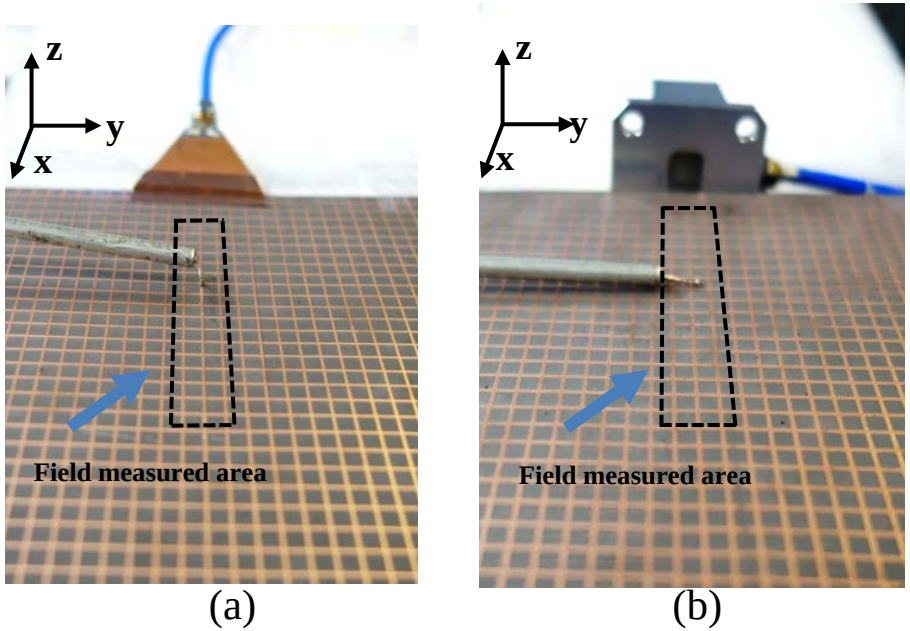
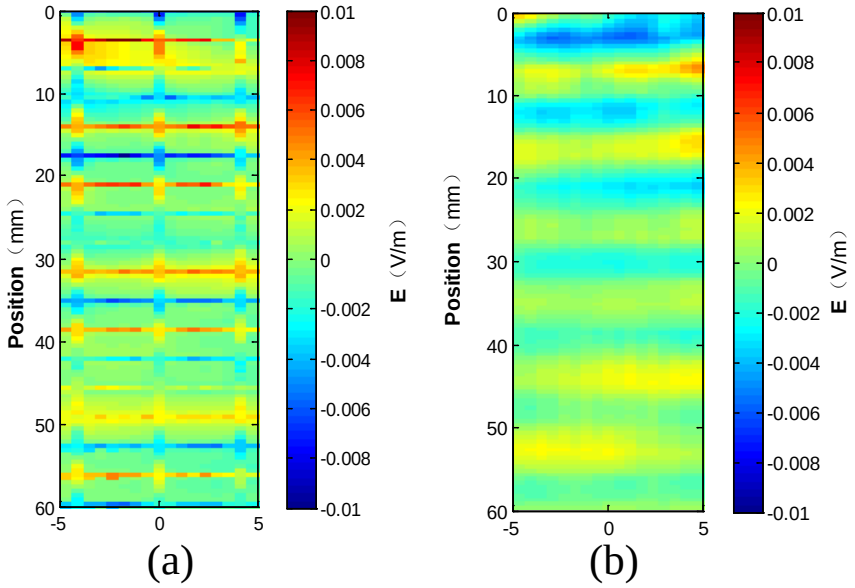
3. Topology I (4)

Field Measurements



(a) (b)

Fig. Near field measurement setup for (a) TM mode and (b) TE mode.



(a) (b)

Fig. (a) Measured E_z . (b) Measured E_y .

- **By implementing the fast Fourier transform algorithm (FFT) to the measured fields for both TM and TE wavenumber calculations.**

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3. Topology I (5)

Dispersion Diagram

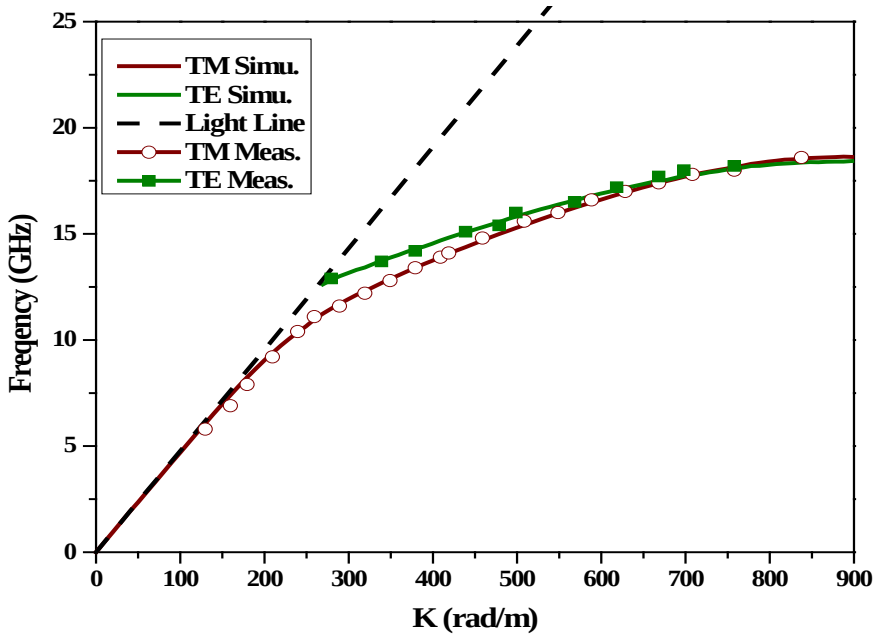

Fig. Simulated and measured dispersion diagram of the loop-wire unit cell.

- **The dispersion curves of the TM mode and TE mode overlap around 18 GHz, which means TM mode and TE mode have the same phase velocity.**

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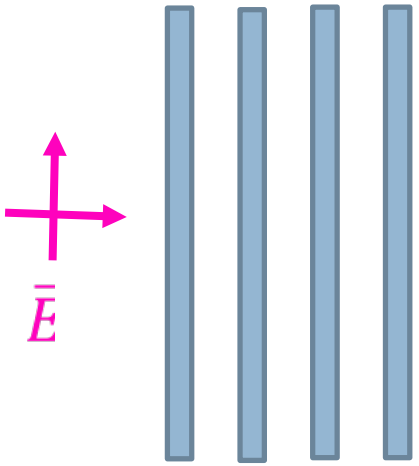
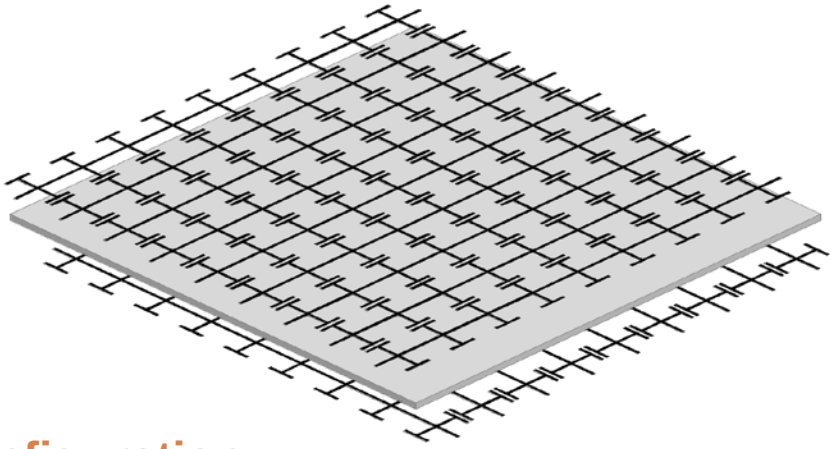
4. Topology II (1)

For an array of continuous, conducting narrow strips, the impedance is either inductive (responsible for the TM mode) or capacitive (responsible for the TE mode), depending on whether the incident wave is polarized parallel to or perpendicular to the edges of the strips, respectively



Conducting strips



Topology configuration:
consisting of two layers. For the top layer, there are gaps in one direction and continuous conducting strips in the orthogonal direction. The bottom layer is created from a 90º rotation of the top layer.

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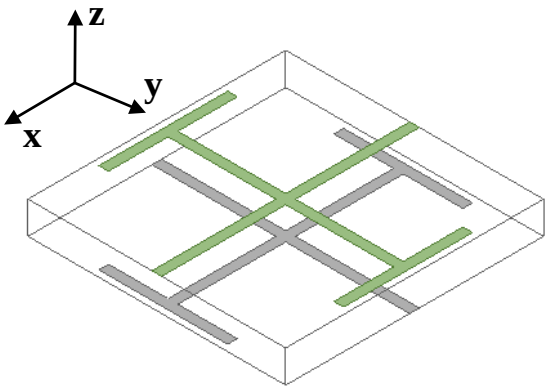
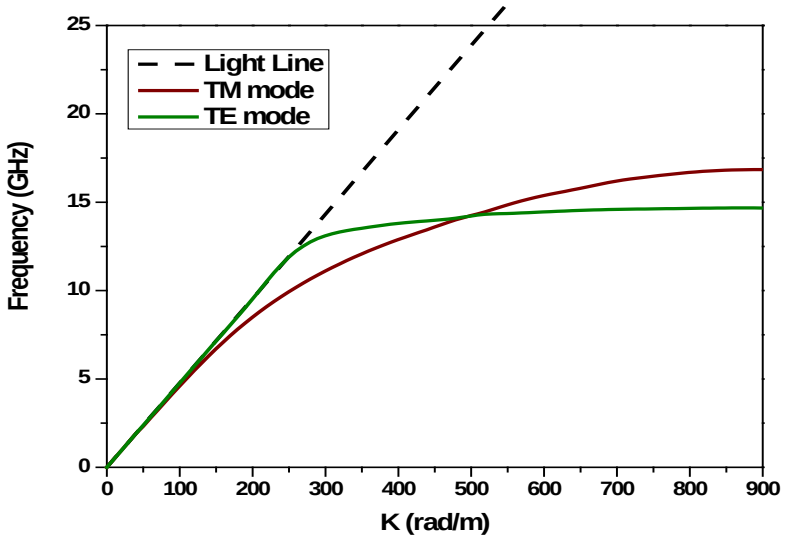
4. Topology II (2)

Unit Cell Configuration

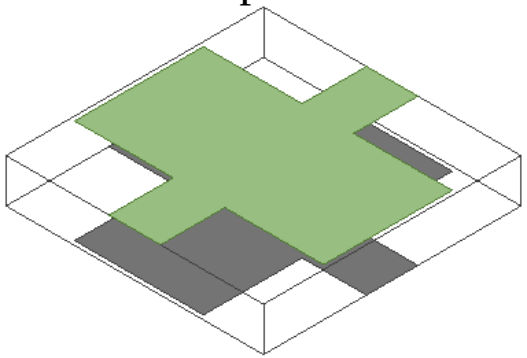


Unit cell configuration

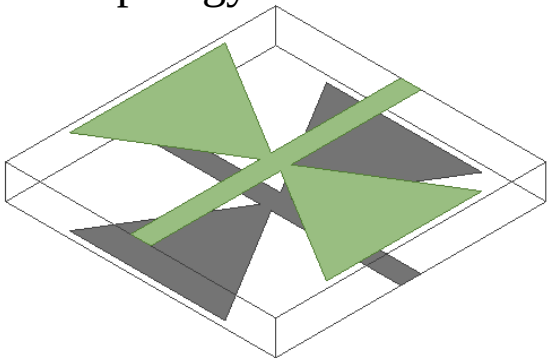


Example of its dispersion curves; TE and TM modes overlap

Different unit-cell shapes can be created based on this topology:



Step-like unit cell



Bow-tie-like unit cell

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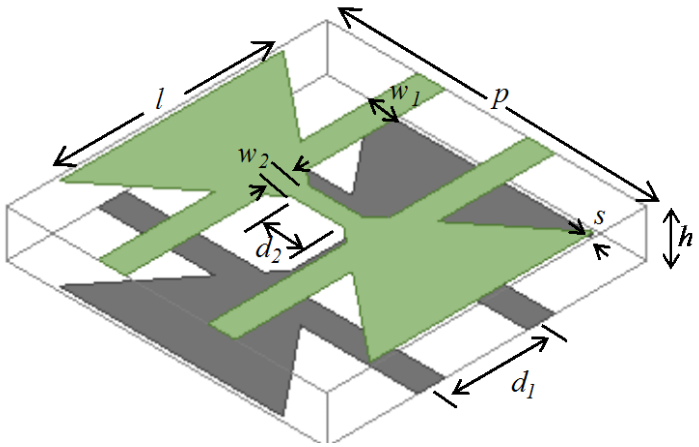
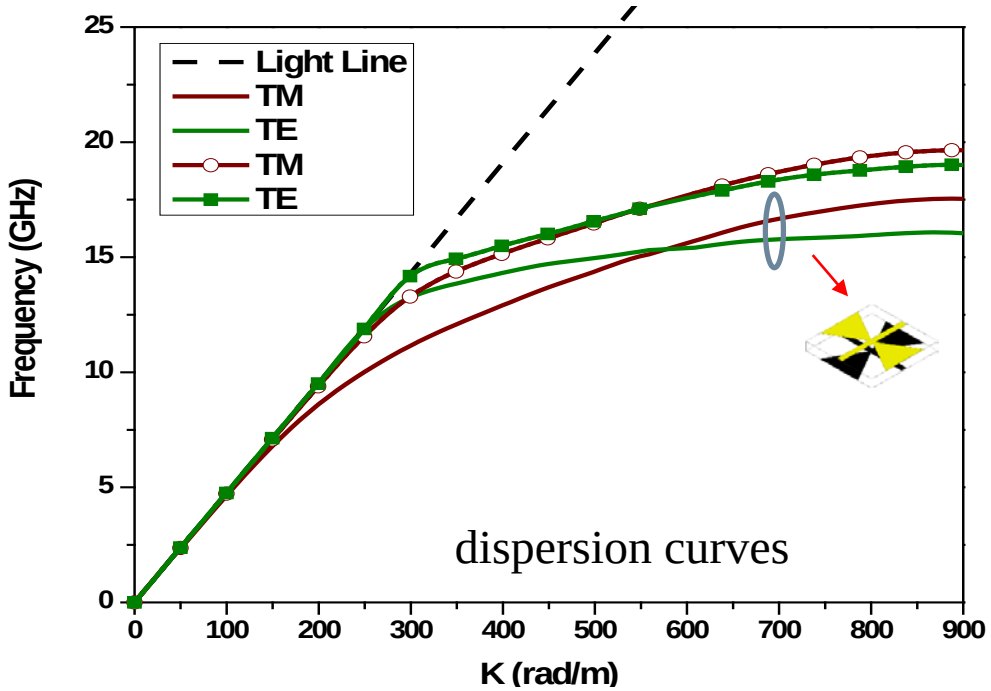
4. Topology II (3)

Modified Bow-Tie-Like Unit Cell Design





The central metal strip was replaced by twin wires separated with a distance of d_1 = 1.2 mm.
The modified bow-tie structure exhibits better performance, because the two modes have almost the same phase velocity over a broad bandwidth than that of the bow-tie-like structure.

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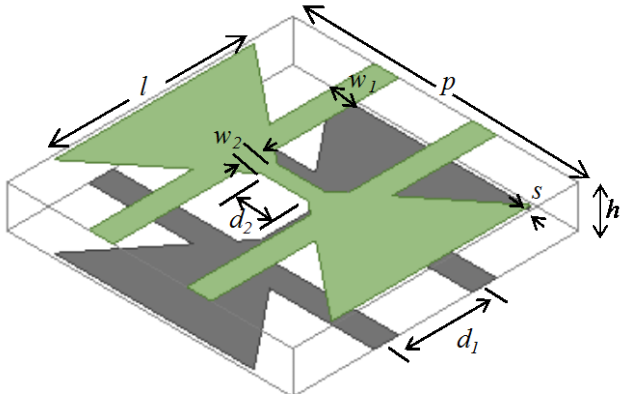
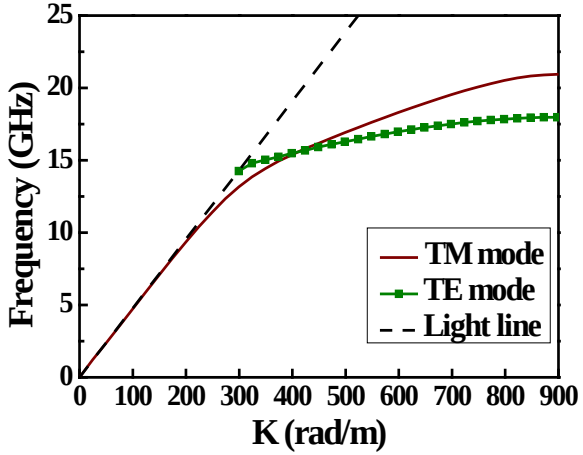
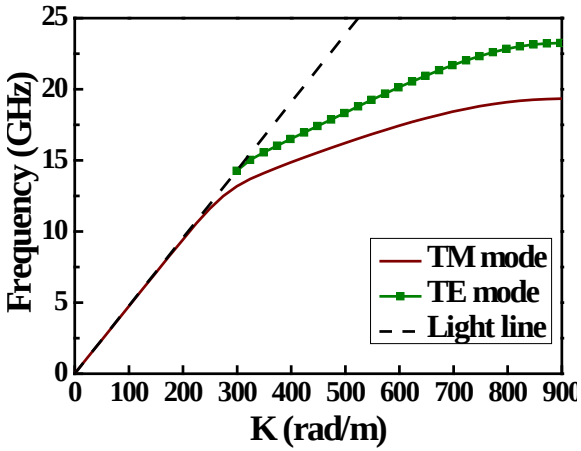
4. Topology II (4)

Parameter Analysis





(a)



(b)

Fig. Dispersion curves with different d_1. (a) d_1 = 0.8 mm. (b) d_1 = 2 mm.

- **The spacing between the twin wires (d_1) has a great effect on its dispersion property.**

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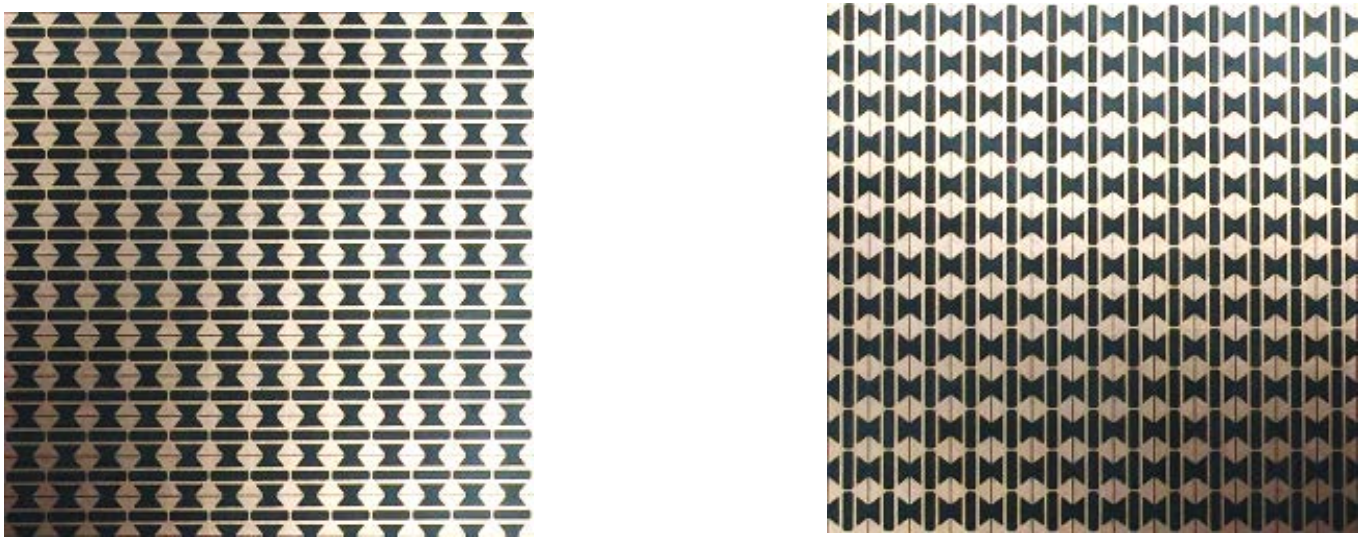
4. Topology II (5)

Fabrication



(a) (b)

Fig. Photograph of a session of the finite-size surface. (a) Top side. (b) Bottom side.

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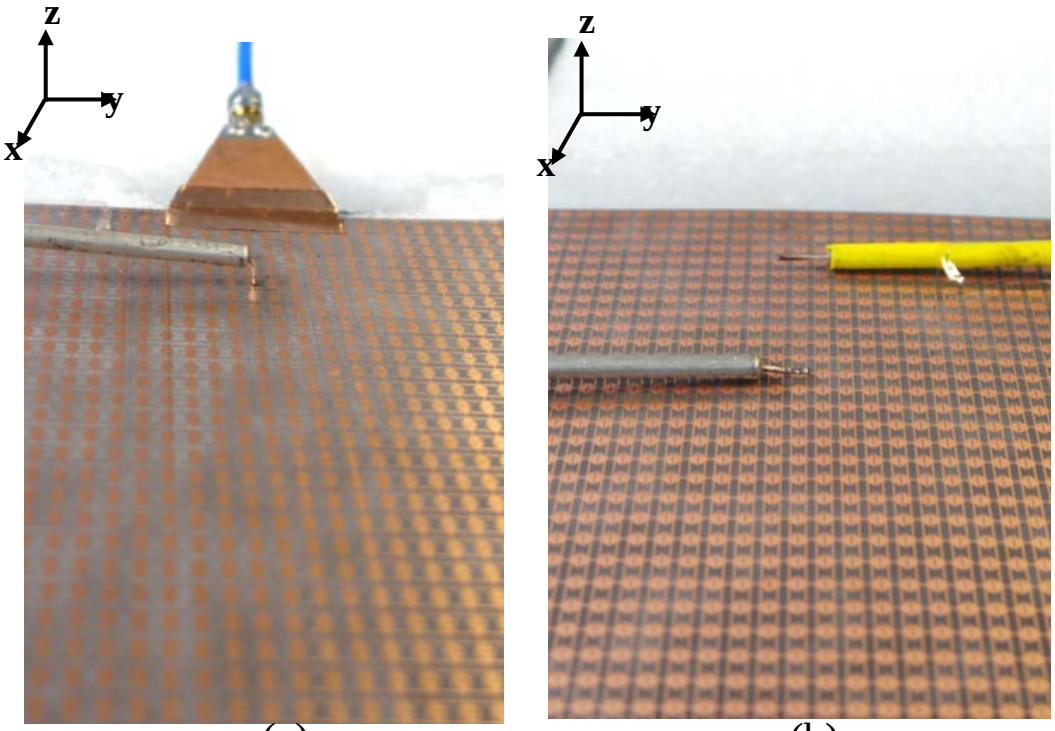
4. Topology II (6)

Measured Results



(a) (b)

Fig. Near field measurement setup for (a) TM mode and (b) TE mode.

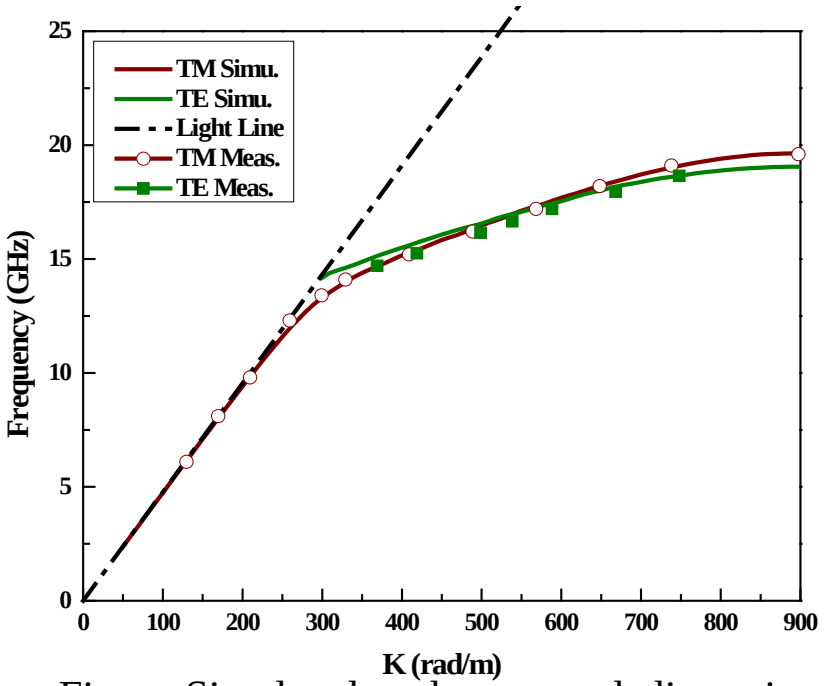


Fig. Simulated and measured dispersion diagram of the loop-wire unit cell.

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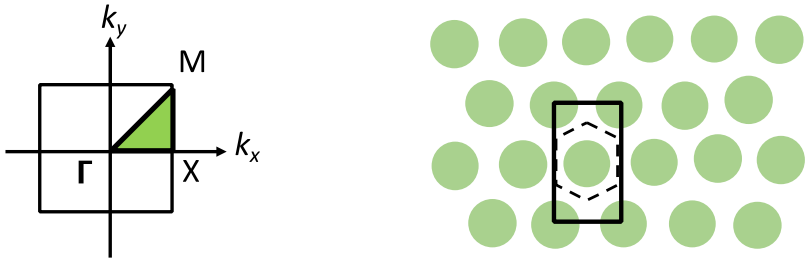
4. Topology II (7)

Effects of Lattice Types on Dispersion Curve

A 2-D **square and hexagonal lattices** are two commonly seen lattice types:



(a) (b)

Fig. Lattice types and their Brillouin zones. (a) Square lattice. (b) Hexagonal lattice.

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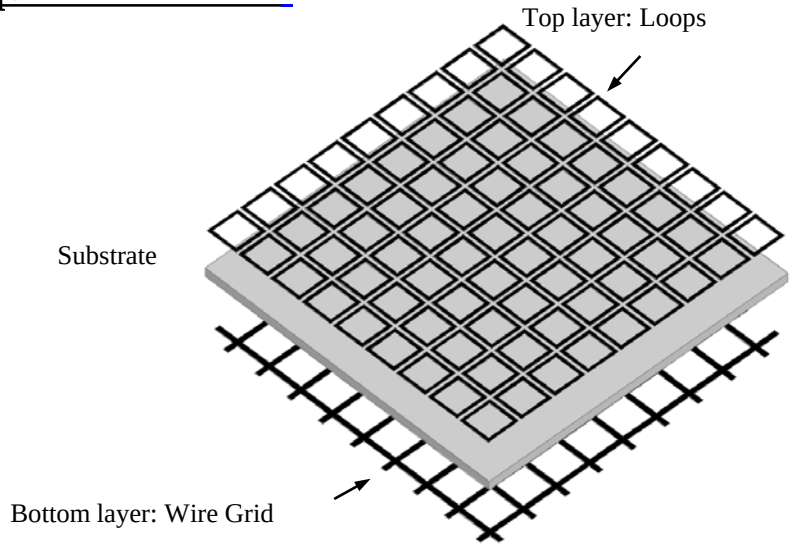
4. Topology II (8)

Square lattices



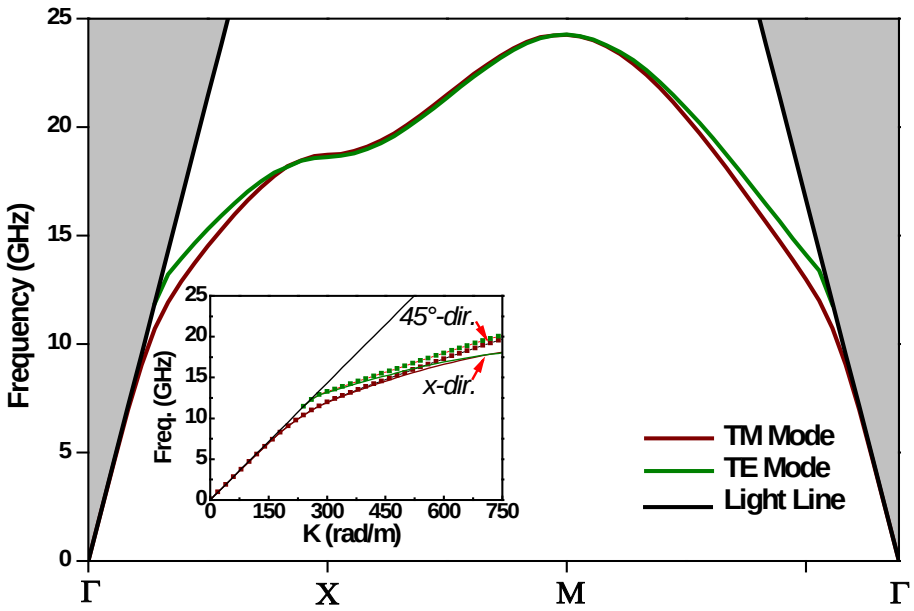


Fig. Dispersion diagram of the first two modes of the loop-wire SWG with square lattice. The sub-graph indicates the dispersion curves along the *x*-direction and the 45° direction.

- **The dispersion curves in the two directions are aligned with each other in the low frequency range. However, with the increase of frequency, the discrepancy deteriorates. As a result, the dispersion curves of the loop-wire SWG with square lattice exhibit great discrepancy when the SWs propagate in different directions along the SWG surface.**

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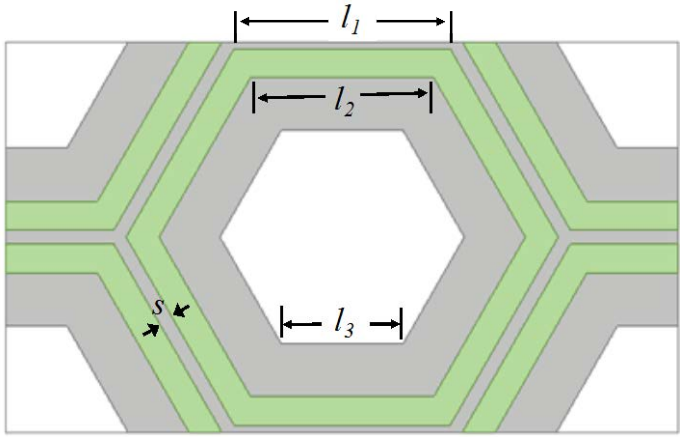
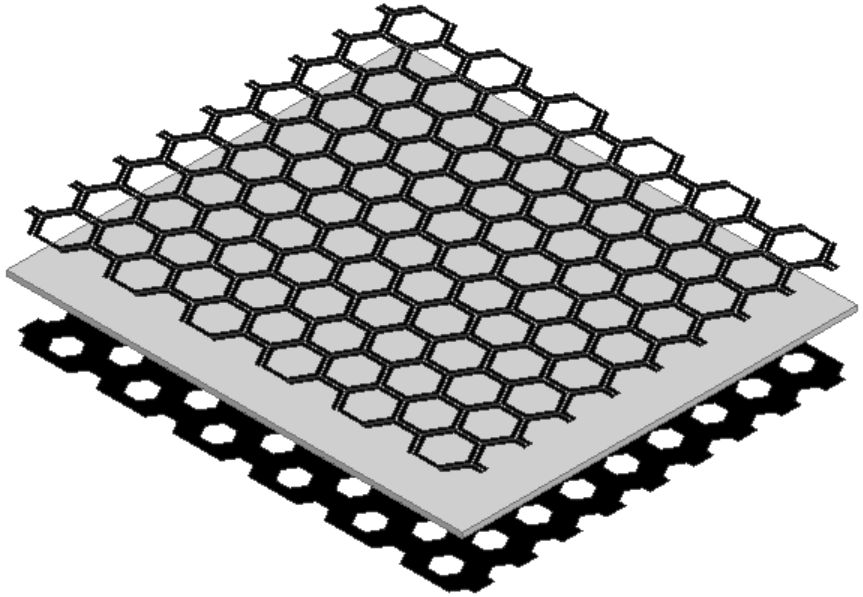
4. Topology II (9)

Hexagonal lattices



(a)



(b)

Fig. Hexagonal loop-wire unit supercell and its SWG configuration with hexagonal lattice. (a) Hexagonal loop-wire unit. (b) Portion of SWG with hexagonal lattice

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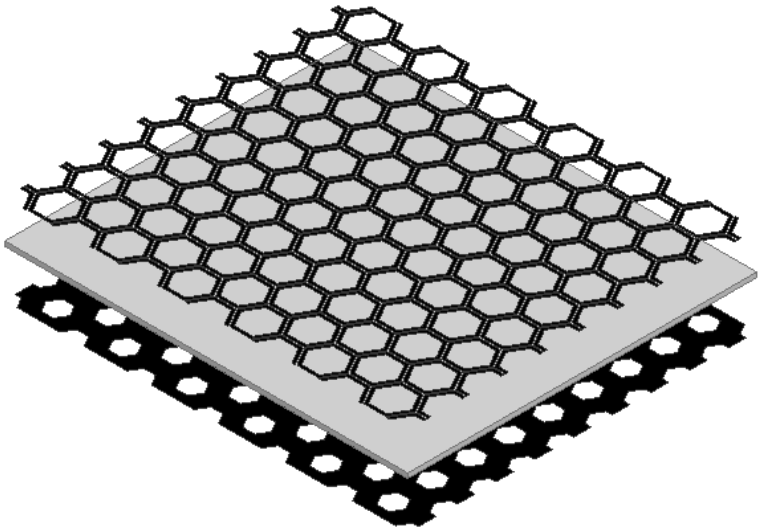
4. Topology II (10)



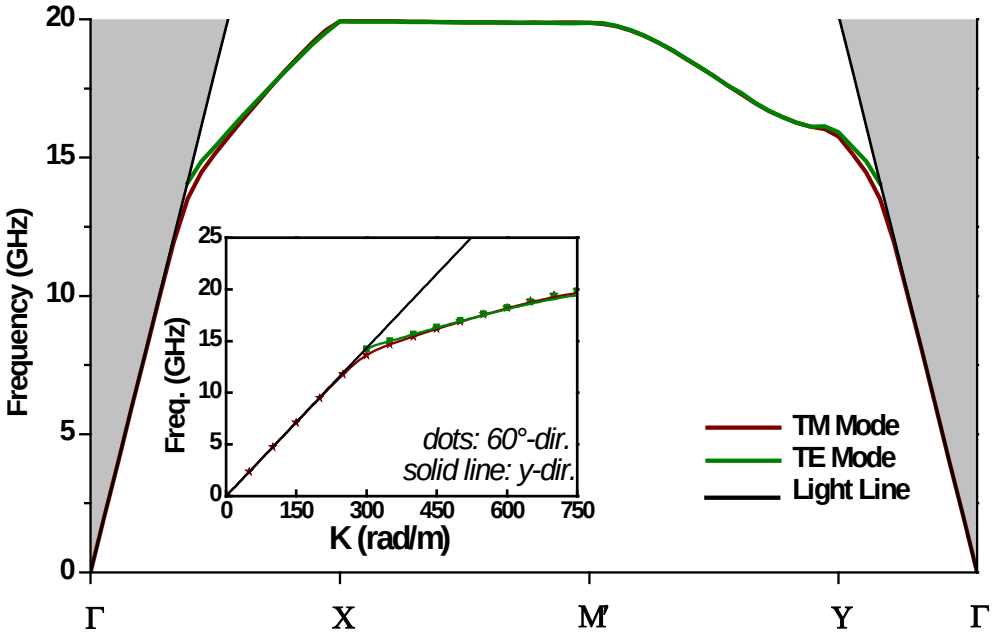


Fig. Dispersion diagram of the first two modes of the loop-wire SWG with hexagonal lattice. The sub-graph indicates the dispersion curves along the *y*-direction and the 60° direction.

- **Conclusion: The proposed hexagonal loop-wire SWG with hexagonal lattice exhibits almost the same dispersion curves when SWs propagate in different directions of the surface. Therefore, SWGs with hexagonal lattice exhibit better performance in the aspect of dispersion property than those with square lattice .**

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5. Conclusion

- **Two SWG topologies** are found to have the property of supporting both TM mode and TE mode with the same phase velocity.
- **The first type** consists of two FSS layers whose dominant modes are TM mode and TE mode, respectively.
- **The second type** is composed of two layers and the bottom layer comes from a 90^{o} rotation from the top layer. For each layer, there are gaps in one direction and continuous conducting strips in the orthogonal direction.
- **Loop-wire SWG** and **modified bow-tie-like** SWG structures are investigated for illustration.
- The effects of **lattice types** on dispersion diagrams are analyzed.

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